

Spectral Study of the WNL Star FSZ35 in the M33 Galaxy

O. Maryeva^{1*} and P. Abolmasov²

¹*Stavropol State University, Pushkina str., 1, Stavropol, 355009, Russia*

²*Sternberg Astronomical Institute, Moscow State University, Universitetsky pr., 13, Moscow, 119992, Russia*

Accepted – . Received – ; in original form –

ABSTRACT

We study and analyse low-resolution spectra of the unordinary late WN star FSZ35 in M33. We classify the object as a hydrogen-rich WN8 star. Using the radiative transfer code CMFGEN, we determine the physical parameters of this object and compare them to the parameters of other WN8 stars including the LBV star Romano’s star during the minimum of brightness. Unlike Romano’s star, the object is fairly stable both spectrally and photometrically, that may be attributed to its more advanced evolutionary stage or lower luminosity. FSZ35 is shown to possess a compact nebula producing faint but detectable [O III] emission. Location of this object at a large distance (~ 100 pc) from the nearest association suggests the object may be one more example of a massive runaway star.

Key words: galaxies: individual: M33 – stars: Wolf-Rayet – stars: supergiants – stars: individual: FSZ35 (M33)

1 INTRODUCTION

Since middle 1990s, radiation transfer codes designed for modeling extended expanding atmospheres became a reliable instrument for studying hot stars with high mass-loss rates. These codes make it possible to calculate the atmospheres of outstanding objects like O-supergiants, Wolf-Rayet (WR) stars and even Luminous Blue Variables (LBV). In particular, the CMFGEN (Hillier & Miller 1998) code was used to model the spectra of η Car (Groh et al. 2010), AG Car (Groh et al. 2009) and AFGL2298 (Clark et al. 2009). CMFGEN and PoWR (Hamann & Gräfener 2003) were used to determine the properties of the majority of the Galactic nitrogen-rich Wolf-Rayet (WN) stars (Crowther et al. 1995; Hamann et al. 2006) including WN stars near the Galactic center (Martins et al. 2007; Hamann et al. 2010).

High-luminosity stars are rare objects, and their studies in our Galaxy are complicated by dust absorption, crowded stellar fields and unknown distances. Therefore, it is important, and sometimes more convenient, to study massive stars in nearby galaxies. Studying WR stars that are probable progenitors of Type Ibc Supernovae and gamma-ray bursts is of especial importance (see review by Crowther (2006) and references therein). It is even more difficult to determine the distances toward Galactic WN8 stars because they can not be associated with clusters or associations (Crowther et al. 1995b; Marchenko et al. 1998). One possible scenario proposed to explain the apparently enigmatic characteristics of WN8 stars is that they are runaways, either ejected

via dynamical interaction from the cores of forming dense star clusters (e.g. Evans et al. (2010)), or accelerated by a slingshot-type mechanism during the supernova explosion of the initial primary component in a binary system (De Donder et al. 1997).

The comprehensive catalogue of Massey & Johnson (1998) lists in total 117 nitrogen-rich Wolf-Rayet stars in M33 (including WN candidates). But models of atmospheres are constructed for only few objects. Parameters of the atmospheres of MCA1-B and B517 were determined with the iterative technique of Hillier (1990) (precursor of CMFGEN) in Smith et al. (1995) and Crowther et al. (1997), respectively. Using the WM-BASIC code (Pauldrach et al. 2001), Bianchi et al. (2004) used the ultraviolet spectra of six known late WN (WNL) stars in M33 to estimate their fundamental parameters: wind terminal velocities, luminosities, effective temperatures, radii, mass-loss rates and C/N abundance ratios. In the current work, we use the CMFGEN code (Hillier & Miller 1998) to study the spectrum of the little-studied WN star FSZ35 in M33.

The object FSZ35 ($\alpha = 01^h 33^m 00^s.20$, $\delta = +30^\circ 30' 15''.2$, (J2000 epoch)) is situated near the association 128 OB¹ in the M33 galaxy 14' away from galactic centre. Projected distance toward the association is 30-40'' or 100-120 pc. Ivanov et al. were the first to obtain photometrical data for this object (IFM-B 174, in their notation) in the U , B , and V bands and publish an identifica-

* E-mail: olga.maryeva@gmail.com

¹ From the catalogue of OB associations by Humphreys & Sandage (1980)

Table 1. Observational log for the SCORPIO data. S/N is signal-to-noise ratio, PA is position angle.

Date	Exposure time [s]	Grism	Spectral range [Å]	$\delta\lambda$ [Å]	S/N	Seeing ['']	Spectral standard star	PA [°]
FSZ35								
4. 10. 2007	900 + 1200	VPHG1200G	4000-5700	5.5	19	1.2	G191B2B	-182
V532								
5. 10. 2007	3 × 900	VPHG1200G	4000-5700	5.5	34	1.1	BD25d4655	-141

tion chart for it (Ivanov et al. 1993). The star is listed in the H α emission-line object catalogue (Fabrika, Sholukhova & Zakharova 1997) as object number 35. In 1998, Massey & Johnson published a list of 22 Wolf-Rayet stars selected by photometry in three non-standard filters: WN ($\lambda 4686$), WC ($\lambda 4650$) and CT ($\lambda 4752$, continuum). Identification was then confirmed spectroscopically (Massey & Johnson 1998). In this work, the star is listed as object E1 and is classified as a Wolf-Rayet star of nitrogen sequence, WN8 subtype. Sholukhova et al. (1999) note similarity between the spectra of FSZ35 and V532 (Romano’s star). The latter is a better studied object located in the outer spiral arm of M33 at a distance of about 17' from the centre. V532 is universally recognized as an LBV star. It demonstrates pronounced photometrical and spectral variability (Kurtev et al. 2001; Polcaro et al. 2003; Maryeva & Abolmasov 2010). Hence we pay especial attention to comparison between these two objects. Similar modeling for V532 will be published in a separate paper (Maryeva & Abolmasov 2011).

This paper is organized as follows. The observational data and data reduction process are described in the next section. We characterise and classify the observed spectrum in Section 3. In Section 4 we describe the basic properties of the CMFGEN code and its main assumptions, while in Section 5 we present and analyse the modeling results. In Section 6 we discuss the results. Finally, in Section 7 we summarize the main points of our work.

2 OBSERVATIONS AND DATA REDUCTION

In this work, we use a spectrum of FSZ35 obtained at the 6m Special Astrophysical Observatory (SAO) telescope². Two exposures, 1200s and 900s in length, were obtained with the SCORPIO multi-mode focal reducer (Afanasiev & Moiseev 2005) in the long-slit mode on October 4, 2007. VPHG1200 G grism was used providing the spectral range of 3950-5500 Å. The data were reduced using the **ScoRe** package for long-slit data reduction, written in IDL especially for SCORPIO long-slit data reduction. This package consists of procedures created by V.Afanasiev, A.Moiseev, P.Abolmasov and O.Maryeva. Package includes all the standard stages of long-slit data reduction process. The final

spectrum has spectral resolution ~ 5.5 Å (weakly dependent on wavelength) and signal-to-noise ratio per resolution element in continuum ~ 20 .

Besides the spectrum of FSZ35, in this work we use a spectrum of Romano’s star obtained at the 6m SAO telescope practically at the same time with the same grating under similar conditions. Details about the spectral data on V532 and data reduction may be found in our recent paper Maryeva & Abolmasov (2010). Basic information about the observational data on both objects is summarized in Table 1.

3 SPECTRAL CLASSIFICATION

Figure 1 shows the spectra of V532 and FSZ35 obtained under similar conditions. The spectral appearance of FSZ35 shows strong similarities with V532. The spectrum of FSZ35 is as rich as the spectrum of V532 in emission lines, but the presence of nebular lines is questionable (see below Section 6) and hydrogen lines are fainter. Table 2 presents the lines detected in the spectrum of FSZ35. Lines of helium and hydrogen in the spectrum of FSZ35 are much broader in comparison with the these lines in the spectrum of V532. For example, FWHM (Full Width at Half Maximum) of H β is 12.0 ± 0.2 and 5.5 ± 0.1 Å for FSZ35 and V532, respectively. For He I $\lambda 4921$, FWHM are 9.5 ± 0.2 and 4.4 ± 0.1 Å.

Using nitrogen and He II lines, we classified V532 in October 2007 as a WN8 star using the classification of Smith, Crowther & Prinja (1994) for WN6-11 stars. Locations of V532 on the diagrams “equivalent width of He I $\lambda 5876$ versus He II $\lambda 4686$ ” and “equivalent width of He II $\lambda 4686$ versus FWHM of this line” are consistent with the WN8 subtype (Maryeva & Abolmasov 2010; Polcaro et al. 2010).

Similar consideration allows to classify FSZ35 as a WN8 as well. Besides this, the N IV $\lambda 4057$ line clearly seen in our spectrum is never present in WN9 spectra, thus excluding FSZ35 identification as a later-subclass object. Unfortunately, our data cover only a limited spectral range from 3900 to 5500 Å. Therefore we can not use the He I $\lambda 5876$ line for spectral classification.

We used a quantitative chemistry-independent criterion based on the FWHM of the He II $\lambda 4686$ line for alternative spectral classification (see, for example, Smith et al. (1995)). Equivalent width (EW) of the He II $\lambda 4686$ line in the spectrum of FSZ35 is 20 Å. FWHM of this line is 10.5 ± 0.5 Å. In Fig. 2, we show the location of V532 and FSZ35 on the diagram of the EW of He II $\lambda 4686$ versus the FWHM of this

² Spectral data were taken from the archive of Special Astrophysical Observatory (SAO) of Russian Academy of Sciences, <http://www.sao.ru/oasis>

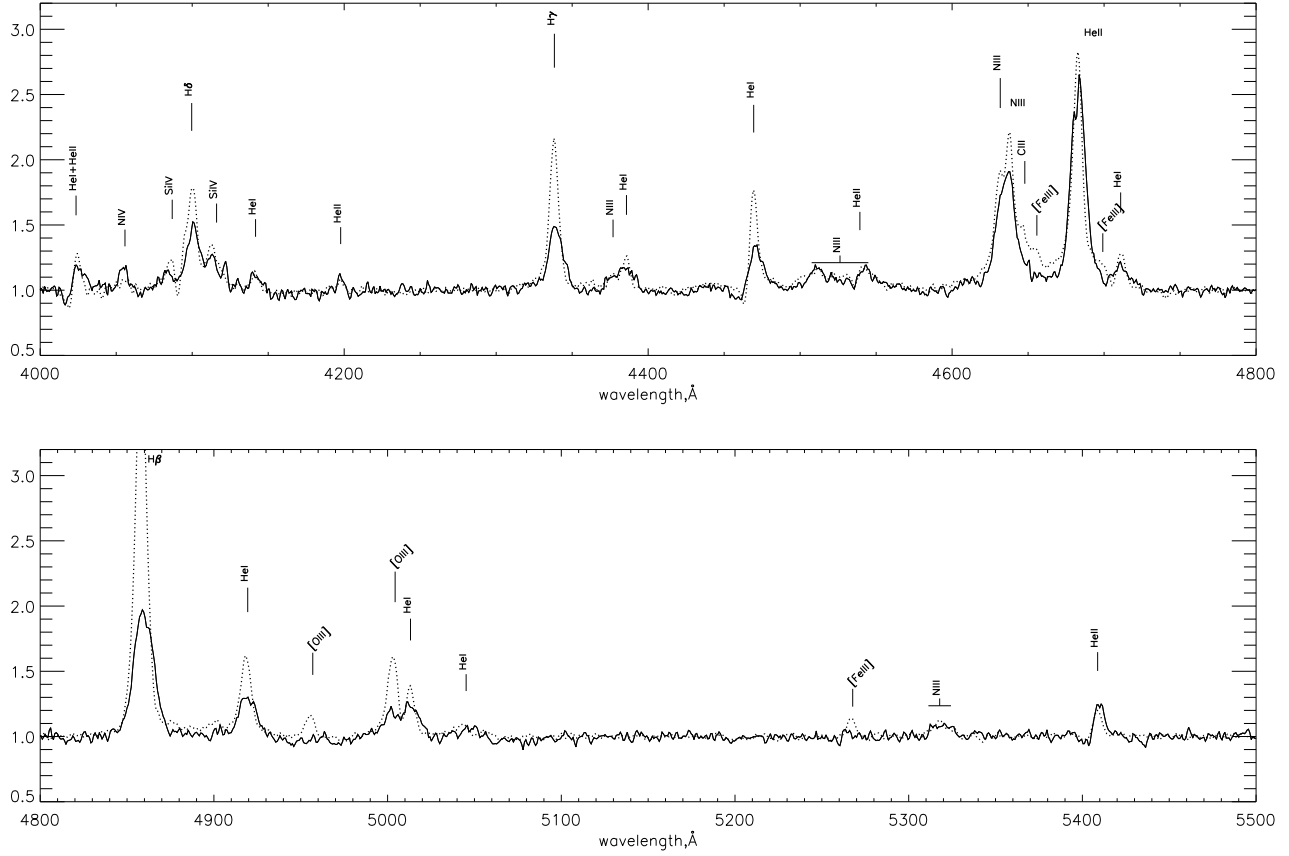


Figure 1. Spectra of FSZ35 (solid line) and V532 (dotted line) obtained in October 2007. The spectra are normalized by the local continuum level.

Table 2. List of emission lines detected in the spectrum of FSZ35. For higher signal-to-noise ratios, equivalent widths (EW) are given.

λ , Å	Ion	EW, Å	λ , Å	Ion	EW, Å
3964.73	He I		4523.60	N III	
3970.08	He I+He II		4530.80	N III	
3994.99	N II		4534.60	N III	
4009.00	He I		4541.60	He II	
4025.60	He I+He II		4547.30	N III	
4057.80	N IV	1.10 ± 0.15	4601.50	N II	
4088.90	Si IV	1.2 ± 0.3	4607.20	N II	
4097.31	N III	4.4 ± 0.4	4613.90	N II	
4101.74	H δ +He II		4621.40	N II	
4103.40	N III		4630.54	N II	
4116.10	Si IV	2.4 ± 0.4	4634.00	N III	7.2 ± 0.1
4120.99	He I		4640.64	N III	4.9 ± 0.1
4143.76	He I	1.0 ± 0.3	4643.09	N II	
4199.80	He II		4650.16	C III	3.3 ± 0.1
4236.93	N II		4685.81	He II	20.0 ± 0.5
4241.79	N II		4713.26	He I	2.8 ± 0.2
4241.79	N II		4861.33	H β	13.4 ± 0.3
4340.47	H γ +He II	5.5 ± 0.4	4921.93	He I	4.1 ± 0.2
4387.93	He I		5001÷5007	N II+[O III]	
4471.69	He I	3.0 ± 0.3	5015.67	He I	2.9 ± 0.2
4510.90	N III	~ 1	5314	N III	
4514.90			5320		
4518.20			5327		
			5411.50	He II	1.8 ± 0.2

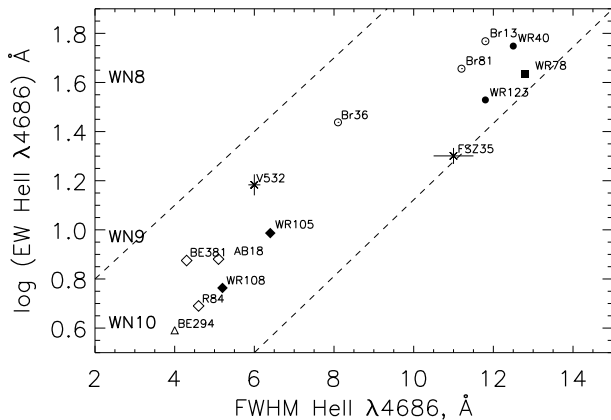


Figure 2. The location of FSZ35 and V532 (October 2007) on equivalent width versus FWHM diagram for the HeII λ 4686 line. Known Galactic (filled symbols) and LMC (open) WN stars are shown for comparison: WN7 by squares, WN8 by circles, WN9 by diamonds, and WN10 by triangles. Data on these objects were taken from Crowther & Smith (1997); Crowther & Bohannon (1997).

line. Position of the object in this diagram is consistent with our identification of FSZ35 as a WN8 star.

We confirm the spectral classification of the object as a WN8 star. This our result also suggests the object is much less variable than V532 that spans a broad range of effective temperatures and luminosities and becomes a late WN star only in deep minima. FSZ35 is thus closer to “quiet” WN stars.

4 MODELING

For our analysis we used the non-LTE radiative transfer code CMFGEN (Hillier & Miller 1998). CMFGEN solves radiative transfer equation for objects with spherically-symmetric extended outflows using either the Sobolev approximation or the full comoving-frame solution of the radiative transfer equation. To facilitate simultaneous solution of the transfer equation and statistical equilibrium equations, partial linearization method is used. To facilitate the inclusion of metal line blanketing in CMFGEN, superlevel approach (Anderson 1989, 1991) is used. In this formalism, levels with similar properties are treated as one and have identical departure coefficients. This allows to save considerable amount of computer memory and time. Recent versions of the code incorporate also the effect of level dissolution, influence of resonances on the photoionization cross section, and the effect of Auger ionization.

Clumping is incorporated into CMFGEN using volume filling factor approach (Hillier & Miller 1999). Filling factor is allowed to depend on radius. By default, the wind is considered homogeneous at the hydrostatic radius and becomes more and more clumped with the wind velocity. Clumping tends to reduce the derived mass-loss rates by a factor of $\sim 3 - 5$ (Marcolino et al. 2007). Unclumped mass loss rate (i. e. calculated not taking clumping into account) is related

to the volume filling factor f by relation $\dot{M}_{\text{uncl}} = \dot{M}_{\text{cl}}/\sqrt{f}$ (see for example Herald et al. (2001)).

Every model is defined by a hydrostatic stellar radius R_* , luminosity L_* , mass-loss rate \dot{M}_{cl} , filling factor f , wind terminal velocity v_∞ , stellar mass M , and by the abundances Z_i of included elementary species. We assumed a constant turbulent velocity of 20 km/s. Its variations do not affect the resulting spectrum much save for the equivalent width of HeII λ 4686 that becomes slightly brighter in more turbulent atmospheres.

5 MODELING RESULTS

Using the model of Romano’s star calculated by Maryeva & Abolmasov (2011) as the seed model we adjusted its parameters to reproduce the observed spectrum of FSZ35. As for V532, H, He, C, N, Si, Fe, O, Ne, Mg, S, Ar, Ca, and Na were included in calculations. We considered only sub-solar iron abundances (between 0.2 and 0.5 solar). Hydrogen lines in the spectrum of FSZ35 are weaker than in the spectrum of V532, suggesting lower H/He values of $\sim 0.6 \div 0.8$ (by number), unlike V532 where hydrogen abundance is estimated as $\text{H/He} \simeq 1.3$.

We increased the effective temperature of the model in order to reproduce the NIV λ 4057 emission present in the spectrum, and then varied the luminosity at a constant effective temperature level to fit the observed V-band luminosity. $V = 18^{\text{m}}.7$ is reported by (Massey & Johnson 1998), in consistence with the observed spectrum slightly hotter than that of V532 in deep minimum. In our calculations we supposed that distance toward M33 is $D = 847 \pm 60$ kpc and the distance modulus is $(m - M) = 24.64 \pm 0.15^{\text{m}}$ (Galletti et al. 2004). We neglected intrinsic extinction of M33, since the object is distant from center of the galaxy. Extinction in the Galaxy is estimated as $E(B - V) = 0^{\text{m}}.029$ (corresponding to $A_v = 0^{\text{m}}.1$ for $R_V = 3.1$) by the NED extinction calculator (Schlegel et al. 1998).

At the next step, we change the mass loss rate and terminal velocity v_∞ . Lower resolution and spectral range do not allow to make reliable estimates of the terminal wind velocity, as we did for V532 in Maryeva & Abolmasov (2010). Terminal velocity given in Table 3 was found by fitting the observed line profiles. The filling factor was set to $f = 0.1$ for all the models. At the last step of the modeling process, we adjust the nitrogen abundance.

In Figure 3 we present the spectrum of FSZ35 and our model. We succeed in achieving good agreement with the observational equivalent widths and profiles of hydrogen lines and singlet lines of neutral helium as well as the line HeI λ 4713.

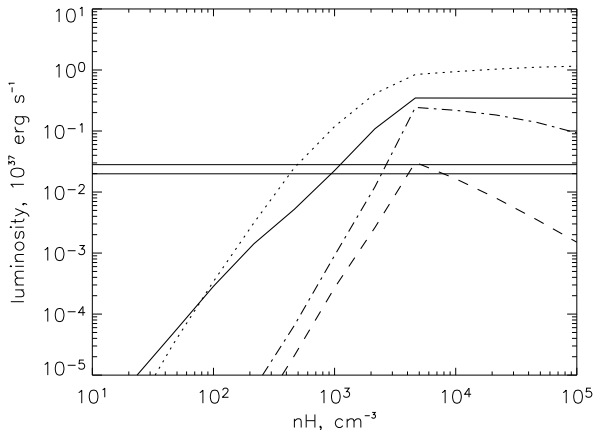
In the best-fit model, H/He ratio is 0.8 and, consequently, mass fraction of hydrogen is $\simeq 0.17$. FSZ35 conforms to the definition of H-rich WN stars (Nugis & Lamers 2000), that must have hydrogen mass fraction > 0.05 . The mass loss rate is $\dot{M}_{\text{cl}} = 2.6 \cdot 10^{-5} M_\odot/\text{year}$ and $\dot{M}_{\text{uncl}} = 8.22 \cdot 10^{-5} M_\odot/\text{year}$. The mass loss rate is given in Table 3 together with other wind and stellar parameters. For comparison, the values of these parameters for some other WN stars taken from the literature are given in the table. Note that the parameters of WR116 and WR89 were calculated using PoWR code (Hamann & Gräfener 2003) while the pa-

Table 3. Derived properties of FSZ35 and V532 in the minimum of brightness (October 2007), and a comparison with similar stars in Milky Way (MW). X_H is mass fraction of hydrogen

Star	Gal.	Sp. type	T_* [kK]	R_* [R_\odot]	$\log L_*$ [L_\odot]	$\log \dot{M}_{\text{uncl}}$ [M_\odot/year]	v_∞ [km/s]	X_H [%]	Ref
WR124	MW	WN8h	32.7	18.0	5.53	-4.2	710	13	[1]
WR116	MW	WN8h	39.8	21.0	6.0	-3.7	800	10	[2]
WR89	MW	WN8h	39.8	26.5	6.2	-4.2	1600	20	[2]
WR40	MW	WN8h	45.0	10.6	5.61	-4.	840	15	[3]
WR16	MW	WN8h	41.7	12.3	5.68	-4.3	650	23	[3]
FSZ35	M33	WN8h	36.5	19	5.76	-4.1	800	16.5	
V532	M33	WN8h	34.0	20.8	5.7	-4.3	360	24	[4]

[1]- Crowther et al. (1999), [2]- Hamann & Gräfener (2003),

[3]- Herald et al. (2001), [4]- Maryeva & Abolmasov (2011)

**Figure 4.** Dependence of nebular line luminosities on the hydrogen density of the putative nebula around FSZ35. Solid is $H\beta$, dotted is $[O\text{ III}]\lambda 5007$, dashed is $[S\text{ II}]\lambda 6717$ and $[N\text{ II}]\lambda 6583$ is shown by a dash-dotted line. Horizontal lines show the measured luminosity of the $[O\text{ III}]$ line (1σ confidence interval).

evolved, or shock excitation also contributes to the emission of the nebula.

Relying on the similarity of the central stars, one may propose that the nebula is similar to M1-67 observed around WR124 (Crowther et al. 1999). Strongest nebular lines in the spectrum of M1-67 are lower-excitation lines such as $[S\text{ II}]\lambda\lambda 6717, 31\text{\AA}$, $[N\text{ II}]\lambda\lambda 6548, 84\text{\AA}$ and $[O\text{ II}]\lambda 3727\text{\AA}$.

Another effect making the putative Wolf-Rayet nebula of FSZ35 hard to detect with the data on hand may be oxygen under-abundance (by a factor of $5\div 10$) reported for M1-67 and other Wolf-Rayet nebulae and related objects (see Esteban et al. (1991) and references therein). Oxygen deficit is a predicted by-product of the CNO cycle and should have (as well as carbon and neon deficits) an amplitude similar to that of nitrogen over-abundance.

6.2 Lack of variability

The spectrum analysed in this work is identical within one spectral sub-class to the spectrum published by Massey &

Johnson (1998). We also classify FSZ35 as WN8. Unlike V532, FSZ35 does not demonstrate any prominent spectral variability.

It is also fairly stable photometrically. V-band magnitude of the object was $18^m.7$ in 1993 (Massey & Johnson 1998) and $18^m.8$ in 2004 (Hartmann et al. 2006), that significantly restricts the possible amplitude of photometrical variability. In the V band, $\Delta m \lesssim 0^m.1$. The lack of photometrical variability may be ascribed to the more advanced evolutionary status of FSZ35 (Meynet et al. 2011).

6.3 FSZ35 as a massive runaway

FSZ35 is located at the distance of about $35''$ (~ 115 pc) from the association OB 128. Suppose that once FSZ35 was a member of the association and was ejected via slingshot-type dynamical interaction. If its peculiar velocity is $\sim 100\text{ km s}^{-1}$, as for WR124 (Sirianni et al. 1998; Marchenko et al. 2010), it could have been expelled from the parent cluster about a million years ago.

Offset positions with respect to the probable parent associations (at distances $\sim 100\text{ pc}$) and unexpectedly large peculiar velocities (of the order $\sim 100\text{ km s}^{-1}$) seem to be common for very luminous and massive stars like V532, FSZ35 and Galactic late WN stars like WR20a and WR124. A scenario was proposed by Gvaramazde & Gualandris (2011) that applies three-body dynamical interaction in the cores of young massive clusters and star-forming regions (similar to 30 Doradus) to reproduce the observed population of massive runaways. This scenario has the disadvantage of relying heavily on the formation of massive stars in the cores of massive young clusters that are, in contrast with LMC, absent in M33, where massive stars are rather formed in dispersed stellar associations.

Instead we would rather propose that very massive stars are formed in dense groups containing several stars each. This is confirmed, for example, by the multiplicity increasing with stellar mass (Zinnecker & Yorke 2007) both in young star clusters and associations. It is reasonable that higher fraction of massive binaries will be accompanied by a higher fraction of massive multiple systems. When formed, such systems are often unstable (Kiseleva et al. 1998) and dynamic interaction between its components should both produce a larger fraction of runaways at these masses (\sim

100 M_{\odot}) and a larger fraction of binaries. The characteristic peculiar velocities ($\sim 100\text{km s}^{-1}$) of these “childhood run-aways” may be reproduced if the initial spatial sizes of the systems are $\lesssim 10^{14}\text{cm}$.

7 CONCLUSIONS

We analyse the optical spectrum of the little-studied WNL star FSZ35 in M33. About 40 spectral lines in the 4000 \div 5500Å wavelength range are identified. We classify FSZ35 as a WN8 star, confirming the result of Massey & Johnson (1998) and put upper limits for the spectral and photometrical variability of this object.

Using non-LTE code CMFGEN we estimate the parameters of FSZ35 (bolometric luminosity, stellar radius, mass loss rate, wind velocity, elementary abundances) and compare them to the corresponding parameters of other WN8 stars including the LBV star V532 during the minimum of brightness. FSZ35 is a H-rich WN8 star where the mass fraction of hydrogen is 17% (H/He=0.8). The best-fit parameters of the model are: luminosity $L = 5.3 \cdot 10^5 L_{\odot}$, mass loss rate $2.1 \cdot 10^{-5} M_{\odot}/\text{year}$, nitrogen abundance N/He = 13.5(N/He) $_{\odot}$, effective temperature at hydrostatic radius $T_{*} = 36470\text{K}$ ($R_{*} = 18R_{\odot}$) and at the Rosseland photosphere $T_{\tau=2/3} = 35160\text{K}$. Derived parameters of FSZ35 atmosphere correspond to a typical WN8 star.

We find that FSZ35 has a surrounding nebula, possibly of low excitation and deficient in oxygen, that decreases its detectability.

Position of FSZ35 at the outskirts of association 128 OB suggests that it was expelled from this association about a million years ago at a velocity of $\sim 100\text{km s}^{-1}$.

Acknowledgements

This work makes use of the data taken from the public archive of the Special Astrophysical Observatory. We wish to thank John D. Hillier for his great code CMFGEN, both comprehensive and user-friendly, that we applied to fit and analyse the data. We also would like to thank the referee Wolf-Rainer Hamann for valuable comments. One of us (P. A.) thanks leading scientific schools grant NSH-7179.2010.2 for support.

REFERENCES

- Afanasiev, V. & Moiseev, A. 2005, *Astronomy Letters*, 31, 194
- Anderson L. 1991, in *Stellar Atmospheres: Beyond Classical Models*, ed. L.Crivellari, I.Hubeny, D.G.Hummer, NATO ASI Ser. C, Vol. 341 (Dordrecht: Kluwer), 29
- Anderson L.S. 1989, *ApJ*, 298, 848
- Bianchi, L., Bohlin, R., Massey, P. 2004, *ApJ*, 601, 228
- Clark, J.S., Crowther, P.A., Larionov, V.M., Steele, I.A., Ritchie, B.W., Arkharov, A.A., 2009, *A&A*, 507, 1555
- Crowther, P.A., Hillier, D.J., Smith, L.J. 1995, *A&A*, 293, 403
- Crowther, P.A., Bohannan, B. 1997, *A&A*, 317, 532
- Crowther, P.A. & Smith, L.J., Hillier, D.J., Schmutz, W. 1995b, *A&A*, 293, 427
- Crowther, P.A. & Smith, L.J. 1997, *A&A*, 320, 500
- Crowther P.A., Szeifert Th., Stahl O., Zickgraf F.-J. 1997, *A&A*, 318, 543
- marchenko
- Crowther, P.A., Pasquali, A., De Marco, O., Schmutz, W., Hillier, D.J., De Koter, A. 1999, *A&A*, 350, 1007
- Crowther, P.A. “Physical Properties of Wolf-Rayet Stars”, arXiv e-print 0610356
- De Donder, E., Vanbeveren, D., van Bever, J. 1997, *A&A*, 318, 812
- Esteban, C., Vilchez, J.M., Smith, L.J., Manchado, A. 1991, *A&A*, 244, 205
- Evans,C.J., Walborn,N.R., Crowther,P.A., Hénault-Brunet,V., Massa,D., Taylor,W.D., Howarth,I.D., Sana,H., Lennon,D.J., vanLoon,J.Th. 2010, *ApJ*, 715, L74
- Fabrika, S.N., Sholukhova, O.N., Zakharova, S.V. 1997, *Byull. Spetz. Astrofiz. Obs.*, 43, 133
- Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., Verner, E. M. 1998, *PASP*, 110, 749
- Galleti, S., Bellazzini, M., Ferraro, F.R. 2004, *A&A*, 423, 925
- Gvaramadze, V. V. & Gualandris, A. 2011, *MNRAS*, 410, 304
- Groh, J.H., Hillier, D.J., Daminieli, A., Whitelock, P.A., Marang, F., Rossi, C. 2009, *ApJ*, 698, 1698
- Groh, J.H., Madura, T.I., Owocki, S.P., Hillier, D.J., Weigelt, G. 2010, *ApJ*, 716, L223
- Hamann, W.-R., Gräfener, G. 2003, *A&A*, 410, 993
- Hamann, W.-R., Gräfener G., Liermann A. 2006, *A&A*, 457, 1015
- Hartman, J. D., Bersier, D., Stanek, K. Z. et al., 2006, *MNRAS*, 371, 1405
- Humphreys, R.M., Sandage, A. 1980, *ApJS*, 44, 319
- Herald, J.E, Hillier, D.J. Schulte-Ladbeck, R.E. 2001, *ApJ*, 548, 932
- Hillier, D.J. 1990 *A&A*, 231, 116
- Hillier, D.J., Miller, D.L. 1998, *ApJ*, 496, 407
- Hillier, D.J., Miller, D.L. 1999, *ApJ*, 519, 354
- Ivanov, G.R., Freedman, W.L., Madore, B.F. 1993, *ApJ*, 85, 89
- Kiseleva, L. G., Colin, J., Dauphole, B., & Eggleton, P. 1998, *MNRAS*, 301, 759
- Kurtev, R., Sholukhova, O., Borrisova, J., Georgiev, L. 2001, *Rev.Mex. AA*, 37, 57
- Liermann, A., Hamann, W.-R., Oskina, L.M., Todt, H., Butler, K. 2010, *A&A*, 524, 82
- Marchenko, S.V., Moffat,A.F.J., Eversberg,T., Morel,T., Hill,G.M., Tovmassian,G.H., Seggewiss,W. 1998, *MNRAS*, 294, 642
- Marchenko, S.V., Moffat, A.F.J., Crowther, P.A. 2010, *ApJ*, 724, 90
- Marcolino, W.L.F., Hillier, D.J. de Araujo, F.X., Pereira, C.B. 2007, *ApJ*, 654, 1068
- Martins,F., Genzel,R., Hillier,D.J., Eisenhauer,F., Pau-mard,T., Gillessen,S., Ott,T., Trippe,S. 2007, *A&A*, 468, 233
- Maryeva, O., Abolmasov, P. 2010, *Rev.Mex. AA*, 46, 279
- Maryeva, O., Abolmasov, P. 2011, *MNRAS* submitted
- Massey, P., Johnson, O. 1998, *ApJ*, 505, 793
- Massey, P., Olsen, K. G. A., Hodge, P. W., Strong, S. B., Jacoby, G. H. et al. 2006, *Astron.J*, 131, 2478
- Meynet,G., Georgy,C., Hirschi,R., Maeder,A., Massey,P.,

- Przybilla, N., Nieva, M.-F. 2011 BSRSL, 80, 266
- Nugis, T., Lamers, H.J.G.L.M. 2000, A&A, 360, 227
- Pauldrach, A.W.A., Hoffmann, T.L., Lennon, M. 2001, A&A, 375, 161
- Polcaro, V.F., Rossi, C., Viotti, R.F., Gualandi, R., Galleti, S., Norci, L. 2010, Astron.J, 411, 193
- Polcaro, V.F., Gualandi, R., Norci, L. 2003, A&A, 411, 193
- Schlegel, D. J., Finkbeiner, D. P., Davis, M. 1998, AJ, 500, 525
- Sirianni, M., Nota, A., Pasquali, A., Clampin, M. 1998, A&A, 335, 1029
- Sholukhova, O.N., Fabrika, S.N., Vlasyuk, V.V. 1999, Astron. Letters, 25, 14
- Smith, L.J., Crowther, P.A., Prinja, R.K. 1994, A&A, 281, 833
- Smith, L.J., Crowther, P.A., Willis, A.J. 1995, A&A, 302, 830
- Zinnecker, H., Yorke, H. W. 2007, ARA&A, 45, 481